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Delayed X-ray emission from fallback in compact-object mergers

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ABSTRACT

When double neutron star or neutron star-black hole binaries merge, the final remnant may comprise a central solar-mass black hole surrounded by a $\sim 0.01-0.1\ M_{\odot}$ torus. The subsequent evolution of this disc may be responsible for short γ-ray bursts (SGRBs). A comparable amount of mass is ejected into eccentric orbits and will eventually fall back to the merger site after ~ 0.01 seconds. In this *Letter*, we investigate analytically the fate of the fallback matter, which may provide a luminous signal long after the disc is exhausted. We find that matter in the eccentric tail returns at a super-Eddington rate and is eventually ($\gtrsim 0.1$ sec) unable to cool via neutrino emission and accrete all the way to the black hole. Therefore, contrary to previous claims, our analysis suggests that fallback matter is *not* an efficient source of late time accretion power and is unlikely to cause the late flaring activity observed in SGRB afterglows. The fallback matter rather forms a radiation-driven wind or a bound atmosphere. In both cases, the emitting plasma is very opaque and photons are released with a degraded energy in the X-ray band. We therefore suggest that compact binary mergers could be followed by an "X-ray renaissance", as late as several days to weeks after the merger. This might be observed by the next generation of X-ray detectors.

Key words: black hole physics — accretion, accretion discs —

1 INTRODUCTION

Close binaries of compact solar-mass objects are expected to form via the evolution of massive star binaries or by dynamical interaction in dense star clusters. Neutron star (NS–NS) binaries have been detected as radio pulsars (e.g. Faulkner et al. 2005), and while black hole–neutron star (BH-NS) or double black hole (BH-BH) binaries have not been observed directly, they are predicted by population synthesis models. The compact objects are expected to merge due to gravitational wave emission, with evolutionary scenarios estimating a local rate of NS–NS mergers $10-100$ times higher than for BH-NS and BH-BH systems (e.g. Belczynski et al. 2007). The final remnant for NS–NS and NS–BH coalescence is generally thought to be a BH of a few solar masses surrounded by a $0.01-0.1\ M_{\odot}$ accreting disc (e.g. Ruffert et al. 1997; Shibata, Taniguchi & Uryu 2003; Rosswog et al. 2004; Faber et al. 2006). The accretion power immediately following the merger is perhaps the ultimate cause of SGRBs (Blinnikov et al. 1984; Eichler et al. 1989; Paczyński 1991). At early times ($\lesssim 0.1-1$ sec), the accreting disc is geometrically thin, effectively cooled by neutrino emission (Popham, Woosley & Fryer 1999). When the accretion rate drops below $\sim 0.1\ \mathrm{M}_{\odot}\mathrm{sec}^{-1}$ — the exact value depending on the accretion parameter α and BH spin (Chen & Beloborodov 2007; Metzger, Piro & Quataert 2008) — the disc becomes radiatively inefficient and super-Eddington accretion drives a substantial outflow (Metzger et al. 2008).

During the dynamical phase of the merger, in which the lighter companion is tidally disrupted, a fraction ($\sim 10^{-2} M_{\odot}$) of the debris receives enough energy to be ejected from the system while a comparable amount remains bound in eccentric orbits (e.g., Rosswog 2007; Faber et al. 2006) and will eventually return to the disc site: *fallback* matter. This weakly bound matter may give rise to interesting phenomena observable on timescales longer than any viscous timescale of the disc. For example, it has been suggested (Lee & Ramirez-Ruiz 2007; Rosswog 2007; Metzger et al. 2008) that it can be responsible for the X-ray flaring, observed in SGRB afterglows on timescales of minutes to hours (e.g. Campana et al. 2006). Unfortunately, numerical investigations have not yet been able to follow the long-term (> minutes) evolution of this eccentric tail, because of time-step limitations (Rosswog 2007).

In this *Letter*, we investigate analytically the fate of

matter falling back onto a recent merger. We argue that energy released during fallback is *not* a promising source of the X-ray flares. The energy liberated during fallback will either lead to a powerful, radiation-driven wind or a more gradually expanding "breeze" that could ultimately form a bound cloud around the merged object. In either case, the expanding gas is so opaque that the radiation is trapped in the expanding flow and degraded to low energies before being released in the X-ray band. We therefore suggest that compact binary mergers might be accompanied by delayed X-ray emission. We assess the detectability of this emission when the merger is localized by either a short γ-ray burst or a gravitational wave signal. A direct observation of the accretion activity would give us valuable information on how compact-object binaries merge.

This *Letter* is organized as follows. We discuss the behavior of the fallback matter in § 2. Then, we consider two possible scenarios for this material as it rebounds: we model a wind in § 3 and a bound atmosphere in § 4. Prospects for detecting the X-ray emission are discussed in § 5 and conclusions are drawn in § 6.

2 ACCRETION BEHAVIOR OF FALLBACK MATTER

In our analysis, we scale our parameters with values appropiate for NS-NS binaries, since these systems are the most common. The encounter of a couple of neutron stars is followed by the formation of a central attractor with typical mass $M_{\rm c} = 2.5\ m_{\rm c}\ M_{\odot}$ (Belczynski et al. 2008), surrounded by an accretion disc that extends initially up to $r_{\rm d} = 10^7 r_{\rm d_7}$ cm (e.g., Ruffert et al. 1997). The weakly bound material, $M_{\rm fb} = 3\times10^{-2} m_{\rm fb}\ M_{\odot}$ (Rosswog 2007), launched into elliptical orbits, will travel as far as its apocenter and eventually come back to its pericenter $r_{\rm p} \simeq r_{\rm d}$. The rate at which this material accretes can be found analytically assuming that the energy distribution with mass is flat: the accretion rate, after a plateau phase at $\dot{M}_{\rm max}$, decreases with time as

$$\dot{M}_{\rm fb}(t) = \dot{M}_{\rm max}\left(\frac{t_{\rm min}}{t}\right)^{5/3}, \tag{1}$$

(Phinney 1989), where the minimum arrival time corresponds to the period of orbits with eccentricity $e \simeq 0$,

$$t_{\rm min} \simeq \frac{2\,\pi\, r_{\rm d}^{3/2}}{\sqrt{GM_{\rm c}}} \simeq 10^{-2}\ m_{\rm c}^{-1/2} r_{\rm d_7}^{3/2}\ {\rm sec}, \tag{2}$$

and the initial accretion occurs at a rate

$$\dot{M}_{\rm max} = \frac{2}{3}\,\frac{M_{\rm fb}}{t_{\rm min}} \simeq 2\ \frac{m_{\rm fb}\ m_{\rm c}^{1/2}}{r_{\rm d_7}^{3/2}}\ {\rm M_{\odot} sec^{-1}}. \tag{3}$$

Even if eq. 1 has been originally derived for tidal distruption of stars in the potential well of a supermassive black hole, numerical calculations by Rosswog (2007) indicate that the $t^{-5/3}$ law also applies to the case we are investigating.

When the fallback matter hits the disc (or the leftover material), its kinetic energy (per unit mass) $v_{\rm fb}^2/2 \simeq GM_{\rm c}(-1/(2a) + 1/r_{\rm d}) \sim GM_{\rm c}/r_{\rm d}$ is converted into heat via shocks. The internal energy of the shocked matter is photon-dominated. Initially, the fallback matter would simply join the disc and accrete onto the central object, because it is effectively cooled by neutrino emission: i.e., the flow rate is *sub*-Eddington with respect to the neutrino luminosity and accretion is possible. The neutrino emissivity $q_{\nu}^{-} = q_{\rm an} + q_{\rm eN}$ is due both to electron-positron pair annihilation $q_{\rm an} \propto T_{\rm sh}^9$ and capture onto nuclei $q_{\rm eN} \propto T_{\rm sh}^6 \rho_{\rm fb}$ (see Popham, Woosley & Fryer 1999, for the analytic approximations). The fallback matter density at $r_{\rm d}$ is $\rho_{\rm fb} = \dot{M}_{\rm fb}/(4\pi r_{\rm d}^2 v_{\rm fb})$, while the temperature to which the gas is shock-heated can be approximately obtained by equating its kinetic energy density at $r_{\rm d}$, $(v_{\rm fb}^2 \rho_{\rm bf}/2)$, to its internal energy density,

$$T_{\rm sh} = \left(\frac{G\,M_{\rm c}\,\rho_{\rm fb}}{r_{\rm d}\,a_{\rm r}}\right)^{1/4} = 3.6\times10^{10}\left(\frac{t_{\rm min}}{t}\right)^{5/12}{\rm K}, \tag{4}$$

where $a_{\rm r}$ is the radiation constant. The BH feeding happens for large enough accretion rates, $\dot{M} > \dot{M}_{\rm ign} \simeq 0.14\ {\rm M_{\odot} sec^{-1}}$, when the cooling time $t_{\rm c} = a_{\rm r} T_{\rm sh}^4/q_{\nu}^{-}$ is shorter than the viscous time at $r_{\rm d}$ $t_{\rm vis} \simeq 0.18\ \alpha_{0.1}^{-1} m_{\rm c}^{-1/2} r_{\rm d_7}^{3/2} \left(H/(r_{\rm d}0.3)\right)^{-2}$ sec. When $t = t_{\rm w} \simeq 5\times10^{-2}$ sec, the accretion rate $\dot{M}_{\rm fb}$ drops below the critical value $\dot{M}_{\rm ign}$ and neutrino cooling becomes inefficient and eventually (when $k_{\rm b} T_{\rm sh} < m_{\rm e} c^2$) switches off completely. The remaining reservoir of mass in the tail is still substantial $M_* = (3/2)\ \dot{M}_{\rm bf}(t_{\rm w})\ t_{\rm w} \simeq 7\times10^{-3} M_{\odot}$ and, unable to accrete onto the black hole, it is likely to be blown off the disc plane.

3 WIND MODEL

The first possible fate for the fallback matter that we consider is the formation of a radiation-driven wind.

The amount of mass entrained in the wind $M_{\rm w}$ and its specific energy are uncertain. One possibility is that the total kinetic energy of fallback matter is deposited unevenly, so that a small fraction of mass ($M_{\rm w} \ll M_*$) can reach a final velocity that exceeds the escape velocity and form a wind. On the other extreme, the wind could have an amount of mass *comparable* to the fallback tail $M_{\rm w} \simeq M_*$, where sufficient internal energy to unbind this weakly bound matter is gained via accretion. Given the range of uncertainty, we will scale our equations adopting $M_{\rm w} = 10^{-3} M_{\rm w_{-3}} M_{\odot}$ and a terminal velocity $v_{\rm t} = 0.3c\ \beta_{0.3}$, where c is the speed of light and we use as guidance the escape velocity $v_{\rm esc} = \sqrt{2GM_{\rm c}/r_{\rm d}} = 0.27c$ at $r = r_{\rm d}$.

To model the wind, we take an initial radius $r_0 \simeq r_{\rm d}$. This is sufficiently close to the sonic radius that we may assume, in first approximation, an outflow with constant velocity equal to its terminal velocity $v_{\rm t}$[1]. The wind, powered by fallback matter, will steadily decrease with time according to eq. 1, $\dot{M}_{\rm w}(t) = 3.4\times10^{23}\ M_{\rm w_{-3}} t_{\rm w_{-1}}^{2/3}\ t_{\rm hr}^{-5/3}\ {\rm g\,sec^{-1}}$, where $t_{\rm w} = 0.1\ t_{\rm w_{-1}}$ sec and the time t since the onset of the wind is in hours ($t_{\rm hr}$). Its matter density then follows from matter conservation,

$$\rho(r,t) = \frac{\dot{M}_{\rm w}(t)}{4\pi r^2 v_{\rm t}}, \tag{5}$$

for radii $r < v_{\rm t} t$. The radiation pressure $P = (1/3)\ a_{\rm r} T^4$ can

[1] For a polytropic wind with $\gamma = 4/3$ the velocity at the sonic point is only $\sqrt{3}$ smaller than the terminal velocity.

be related to ρ by the polytropic relation, with index 4/3. Therefore, the temperature decreases slowly as

$$T(r,t) \propto P^{1/4} \propto r^{-2/3} t^{-5/12}. \quad (6)$$

The radiation transported with the wind is mostly liberated at the trapping radius $r_{\rm tr}$ where the diffusion timescale for photons equals the expansion timescale. Beyond this radius, the luminosity is transported by radiative flux up to the photosphere, where the optical depth $\tau \sim 1$. In our case $\beta \sim 0.3$ or higher, therefore the trapping radius is very close to the photospheric radius and we will ignore in the following the radiative layer. The optical depth for electron scattering $\tau \simeq \rho\kappa r$ is computed with a Thomson opacity $\kappa = 0.2\ \kappa_{0.2}$, that we scale with the value appropriate for a flow composed solely of α-particles. The electron density is, in fact, uncertain: it depends mainly on the initial composition of the wind at $r_{\rm d}$[2], which includes α-particles and free baryons. For a neutron-rich composition, $\kappa < 0.2$. The nucleosynthesis in the wind does not change the free electron density, since temperatures are high enough for the recombined helium to be fully ionized. The trapping radius then reads :

$$r_{\rm tr} = \frac{\dot M_{\rm w} \kappa}{4\pi c} \simeq 1.8 \times 10^{11}\ \kappa_{0.2}\ M_{\rm w_{-3}}\ t_{\rm w_{-1}}^{2/3}\ t_{\rm hr}^{-5/3}\ {\rm cm}. \quad (7)$$

Conservation of energy $1/2 \dot M_{\rm w} v_{\rm t}^2 \approx 16\pi (a/3) T_0^4 r_{\rm d}^2 v_{\rm t}$ allows us to solve for the central temperature, $T_0(r_{\rm d}, t) \simeq 10^8\ \beta_{0.3}^{1/4}\ M_{\rm w_{-3}}^{1/4}\ t_{\rm w_{-1}}^{1/6} / r_{\rm d_7}^{1/2} t_{\rm hr}^{-5/12}$ K, and from eq. 6 we can derive the temperature at the trapping radius

$$T_{\rm tr}(r_{\rm tr}, t) \simeq 1.5 \times 10^5 \left(\frac{\beta_{0.3}^{1/4} r_{\rm d_7}^{1/6}}{\kappa_{0.2}^{2/3}\ M_{\rm w_{-3}}^{5/12}\ t_{\rm w_{-1}}^{5/18}} \right) t_{\rm hr}^{25/36}\ {\rm K}. \quad (8)$$

The emission from the trapping radius of the wind becomes harder with time while the luminosity, $L_{\rm tr}(r_{\rm tr}, t) = \frac{16\pi}{3}\ a T_{\rm tr}^4\ v_{\rm t}\, r_{\rm tr}^2$, decreases,

$$L_{\rm tr}(r_{\rm tr}, t) \simeq 2 \times 10^{40} \beta_{0.3}^2\ r_{\rm d_7}^{2/3} \kappa_{0.3}^{-2/3} M_{\rm w_{-3}}^{1/3}\ t_{\rm w_{-1}}^{2/9}\ t_{\rm hr}^{-5/9}\ {\rm erg\,sec^{-1}}. \quad (9)$$

When $r_{\rm tr} = r_{\rm d}$,

$$t_{\rm x} \simeq 14.9 \left(\frac{\kappa_{0.2}\ M_{\rm w_{-3}}}{r_{\rm d_7}} \right)^{3/5} t_{\rm w_{-1}}^{2/5}\ {\rm days}, \quad (10)$$

the thermal emission has a temperature of

$$T_{\rm x}(r_{\rm d}, t_{\rm x}) \simeq 9 \times 10^6 \left(\frac{\beta_{0.3}}{r_{\rm d_7} \kappa_{0.2}} \right)^{1/4}\ {\rm K}, \quad (11)$$

and a luminosity

$$L_{\rm x}(r_{\rm d}, t_{\rm x}) \simeq 7.5 \times 10^{38} \beta_{0.3}^2 r_{\rm d_7} \kappa_{0.2}^{-1}\ {\rm erg\,sec^{-1}}. \quad (12)$$

We note that in eq. 11 and eq. 12 the only dependences are on the initial radius, the terminal velocity and the opacity. The dependence is particularly weak for $T_{\rm x}$ because, when $r_{\rm tr} = r_{\rm d}$, the accretion rate is set only by the size of the launching region and by the opacity, (see eq. 7). Therefore $L_{\rm x} \simeq \dot M_{\rm w} v_{\rm t}^2 \propto r_{\rm d}\, v_{\rm t}^2/\kappa \propto r_{\rm d}^2 T_0^4 v_{\rm t}$. We stress the important role of the wind composition, equivalently of the electron fraction. For an extreme proton-to-neutron ratio of 0.1, $\kappa \simeq 0.04$ and the X-ray emission ($T_{\rm tr} \geqslant 10^6$ K) starts at $t_{\rm x} \simeq 3$ hr with a luminosity $L_{\rm tr} \simeq 3.4 \times 10^{40}$ erg/sec.

The emission from the wind will switch off when the whole energy supplied by the wind can be accreted ($\dot M_{\rm fb} \simeq M_{\rm edd} \simeq 7 \times 10^{18}$g/sec). This is a long time of the order of ~ 3 months. However, when $L_{\rm x}$ drops below $\sim L_{\rm x}/2$, the X-ray emission is likely to be undetectable. This happens for $t/t_{\rm x} \gtrsim$ a few.

[2] In principle the neutrino/antineutrino luminosities from the disc can change the proton-tp- neutron ratio in the flow. However, at timescales of interest to us, the neutrino emission has died off.

4 ATMOSPHERE MODEL

Another scenario may be envisaged where a bound atmosphere forms around the central object. This can happen, if the outflowing gas retains the same amount of energy per unit mass that the eccentric tail had. This gas would still be bound to the central BH: it would start expanding from $r_{\rm d}$ nearly isotropically until it reaches a radius r_*, where its internal energy is $\sim$ half its potential energy. After a few seconds, this inflated gas cloud has a nearly constant mass $M_* \sim \dot M_{\rm fb}(t_{\rm w}) \times t_{\rm w} \simeq 4.6 \times 10^{-3} {\rm M}_\odot$ and radius r_*, since most of the mass M_* is injected around $t \sim t_{\rm w}$. We can estimate the radius r_* through $G M_{\rm c} M_*/(2r_*) = \int_{r_{\rm d}}^{\infty} G M_{\rm c}/(2a)(dm/da)\, da$, where a is the semi-major axis of the particle orbits in the eccentric tail. Since the distribution of specific orbital energy $\epsilon = -G M_{\rm c}/(2a)$ with mass is constant $dm/d\epsilon \simeq M_*/\Delta\epsilon$, where $\Delta\epsilon \sim G M_{\rm c}/r_{\rm d}$ is the extra energy gained by M_* via the tidal torque, we can solve the integral and find $r_*/r_{\rm d} \simeq \Delta\epsilon/(G M_{\rm c}/(2 r_{\rm d}))$. We conclude that r_* is of the same order as $r_{\rm d}$. This reflects the fact that most of the mass is at small a. We choose to parametrize $r_* = 10\ r_{\rm d} = 10^8\ r_{*8}$ cm.

We can then calculate the cloud's mean properties. Its mean density is $\rho_* = 2.2 \times 10^6 r_{*8}^{-3}$ g cm^{-3} and the temperature can be derived equating its internal energy density (in radiation and gas) with $G M_{\rm c} \rho_*/(2 r_*)$. Radiation pressure is ~ 5 times higher than gas pressure and temperature decreases linearly with the cloud radius, $T \simeq 4.6 \times 10^9 r_{*8}^{-1}$ K (while the pressure ratio remains constant). The gas cloud is in hydrostatic equilibrium, since it changes its properties on a time scale $M_*/\dot M_* \simeq 4 \times 10^6$ sec $t_{\rm hr}^{5/3}$, much longer than the dynamical timescale $t_{\rm dy} \simeq 2.6$ sec $r_{*8}^{3/2}$. The rotational energy may be neglected, being a factor $\sim (r_{\rm d}/r_*)$ times smaller than the internal energy. On timescales of interest, the cloud does not deflate via radiative losses, since the diffusion time is very long, $t_{\rm diff} = r_*^2 \rho_* \kappa / c \sim 4600\ r_{*8}^{-1}$ yrs. The merged object is thus surrounded and obscured by a persistent source, emitting at the Eddington limit

$$L_{\rm ph} = L_{\rm edd} = \frac{4\pi G M_{\rm c}\, c}{\kappa} = 6.2 \times 10^{38} \kappa_{0.2}^{-1}\ {\rm erg\ sec^{-1}}, \quad (13)$$

at a temperature $T_{\rm ph} \simeq 3.1 \times 10^6 r_{*8}^{-1/2}$K.

5 DETECTION PROSPECTS

5.1 X-ray signal

After a few minutes, the photons escaping from the wind are in the ultraviolet band and after an hour or so in the extreme ultraviolet (EUV). This emission is strongly absorbed and unlikely to be observed. At later times $t \simeq t_{\rm x}$, however,

the emission should peak in soft X-ray, with a luminosity $\sim L_{\rm edd}$ (eqs. 12 and 13) and a thermal spectrum with temperature ~ 0.8 keV (eq. 11). In the case that an opaque cloud surrounds the merged object, we have comparable luminosity, emitted at a temperature that depends on the extension or the atmosphere: for simplicity, we consider here the case in which the emission is at ~ 0.8 keV, corresponding to $a \sim 5 \times 10^7$ cm. The main difference with the wind case is that this emission should be persistent.

Under favorable environmental conditions, the emission may be observable. If the merger occurs in a galactic halo or even in the intergalactic medium, absorption should be moderate. Moreover, those locations may not be polluted by contaminating soft X-ray sources. Finally, compact-object mergers should not be accompanied by a bright supernova explosion, eliminating another possible co-located X-ray source.

An Eddington luminosity yields an unabsorbed flux at redshift z of $F = 3.3\times 10^{-16}\,(0.03/z)^2$ erg cm^{-2}sec^{-1}, where we have approximated the luminosity distance at redshift z as $D_{\rm l}(z) = \; 4.2 \times 10^3 (H_o/71)^{-1}\; z$ Mpc. Simulating the response of different current and future instruments [3], allows us to determine the expected count rate as a function of redshift. Assuming $N_H = 10^{20}{\rm cm}^{-2}$ (Galactic and intrinsic to the host galaxy) and a black body spectrum, we get a count rate $\phi = K_{\rm in}\left(\frac{0.03}{z}\right)^2$ cts sec^{-1}, where $K_{\rm in} \simeq 5.4\times 10^{-5}$ for *XMM*, $K_{\rm in} \simeq 4.6 \times 10^{-5}$ for *Chandra*, $K_{\rm in} \simeq 4.5 \times 10^{-3}$ for *XEUS* and $K_{\rm in} \simeq 1.1 \times 10^{-3}$ for *Con-X*.

Fig. 1 shows that X-ray detection is most likely to be feasible with the next generation of instruments. The proposed missions *Con-X* and *XEUS* will be able to collect $\gtrsim 10$ cts or more in a 10^5 sec exposure from mergers occurring as far as $z \simeq 0.1$ and $z \simeq 0.2$ respectively. The local merger rate of NS-NS is estimated to be $\sim 0.8 - 10 \;\; \times 10^{-5}{\rm yr}^{-1}$ per Milky Way galaxy (Belczynski et al. 2007; Kim, Kalogera & Lorimer 2006)[4]. If half of those systems eventually merge in the halo, their rate is $\sim 0.4 - 5 \;\; \times 10^{-7}$mergers yr^{-1}Mpc^{-3}, where a number density of 0.01 galaxies Mpc^{-3} as been assumed (O'Shaughnessy, Belczynski & Kalogera 2008). Combining the NS-NS merger rate and the instrument observable volumes, we predict that *Con-X* could observe $\sim 13 - 156$ mergers yr^{-1} while the expected rate for *XEUS* is $\sim 100 - 1251$ mergers yr^{-1}.

5.2 Merger localization

In order to detect the X-ray emission, it is necessary to localize the merger. In the following, we discuss two possibilities.

5.2.1 Short GRBs

Coalescence of compact objects (especially NS-NS) are possible candidates as progenitors of SGRBs (see Nakar 2007, for a review). Therefore, in principle, a binary coalescence can be localized via a short burst, though there may be limitations. First, the local observed rate is estimated to be ~ 100 times smaller than the local rate of compact object mergers. The discrepancy is mostly credited to the geometrical beaming of the burst jet. Moreover, the *observed* redshifts range typically between $0.1 - 1.5$. However, the distances of these sources could only be measured for a handful of cases in the last few years. Despite this, it is reasonable to assume that short GRBs should also explode closer to us, if they are indeed produced by NS-NS mergers, and that some selection effects are preventing us from measuring their redshifts. When a short GRBs with $z \lesssim 0.2$ should be localized, the X-ray emission from the wind or the atmosphere could be brighter than the X-ray afterglow around two weeks later.

5.2.2 Gravitational waves as signposts

The gravitational wave signal is a more promising signpost for mergers. This is because this signal should be associated with any coalescence of compact objects, unlike the beamed γ-ray emission from SGRBs. An instrument such as *advanced LIGO*[5] should be able to detect mergers of two neutron stars to a distance of $z \sim 0.07$: this implies a detection rate for *XEUS* and *Con-X* of $4 - 54$ mergers yr^{-1}. Advanced *LIGO* will be, in fact, more sensitive to NS-BH binaries, which should be visible up to $z \simeq 0.15$. Since the Galactic merger rate for these systems is $0.1 - 5 \times 10^{-6}$ yr^{-1} per galaxy (Belczynski et al. 2007), *XEUS* is expected to detect $1 - 53$ such mergers per year, while *Con-X* less than 15 per year.

The main limitation seems to be how accurately the merger position could be localized. Current estimates suggest that a network of non-collocated advanced interferometers — such as advanced *LIGO*, advanced *VIRGO*[6] and *LCGT*, Kazuaki et al (2006))—will be able to detect inspiraling binaries at the redshifts of interest and localize them at a degree level (Sylvestre 2003). This is enough for an optical but not for an X-ray follow-up. However, **with a solid angle error** ten times smaller, we can identify a region of the sky with only one local galaxy with redshift $z \lesssim 0.05$; for a galaxy at $z \lesssim 0.15$, the localization error should be, instead, a few hundreds times smaller. The source distance maybe be obtained directly from the gravitational signal (Abbot at al. 2008). This would greatly help the search for the X-ray fallback signal.

6 DISCUSSION AND CONCLUSIONS

In this *Letter*, we investigate the possible fate of fallback matter associated with mergers of compact objects, where a disc is formed by disruption of a NS. Matter flung to highly eccentric orbits will eventually come back to the disc at a super-Eddington rate, converting its kinetic energy into heat via shocks, and will be unable to cool by neutrino emission. Contrary to previous claims, we think that this implies that fallback matter *cannot* accrete all the way to the central

[3] http://heasarc.gsfc.nasa.gov/Tools/w3pimms.html
[4] The quoted numbers are the minimum and maximum theoretically estimated numbers in Belczynski et al. (2007). The main source of uncertainty is the treatment of the "common envelope" channel to compact-object formation.

[5] http://www.ligo.caltech.edu/advLIGO/
[6] http://wwwcascina.virgo.infn.it/advirgo/

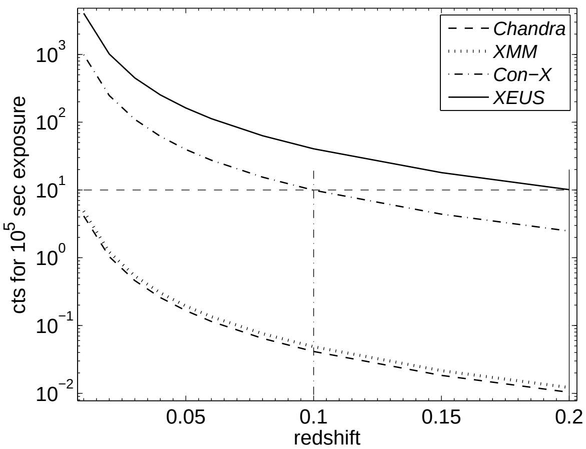

Figure 1. Counts for an exposure of 10^5 sec for the X-ray telescopes quoted in the legend. The maximum distance for which they collect more than 10 couts (horizontal solid line) is indicated by the corresponding vertical lines.

object and be responsible for the late energy injections observed in GRB afterglows. Rather, the fallback matter is likely to be blown off the disc plane, leading to the formation of a radiation-driven wind or a bound atmosphere. For the wind case, we have analytically calculated the time evolution of the temperature and luminosity at the trapping radius: while the luminosity decreases (eq. 9), the wind photosphere becomes hotter (eq. 8). At first, the emission is in the EUV band and absorption will likely prevent us from observing it. After one or two weeks, the emission finally peaks in the soft X-ray band and the wind activity can be observed. The bound cloud is radiation pressure-dominated and emits at the Eddington limit in soft X-rays, if the atmosphere does not extend much further than 10^8 cm. We note that our estimates of luminosities are conservative: factors such as a smaller electron fraction in the ejected plasma and moderate geometrical beaming can substantially increase the expected luminosity.

We also discuss detection prospects for this delayed X-ray activity. Our inspection indicates that only in fortuitous circumstances could the X-ray emission be detected with current instruments, while the planned missions (such as Con-X and XEUS) have a better chance § 5.1. Then, the main limiting factors will not be the X-ray detector capability, but rather the tool for localizing the merger § 5.2. On the one hand, short γ-ray bursts can be easily detected and localized in the whole volume where instruments like *Con-X* and *XEUS* can observe the X-ray emission; however, they are estimated to occur at a rate that is ~ 100 times smaller than the rate at which compact binaries merge. On the other hand, the planned advanced gravitational wave interferometers should be able to detect a signal from any such a merger but within cosmic distances smaller than the maximum distance that *Con-X* and *XEUS* can reach. Moreover, X-ray follow up would require better localization precision than currently estimated.

The net result is that between a few to a few tens of detections per year are expected by *XEUS* with a follow-up of a short GRB. Assuming sufficiently good localization, repointing after a gravitational signal detection can result in $\sim 4-54$ wind detection per year from NS-NS mergers, for both *Con-X* and *XEUS*. Furthermore for *XEUS*, there is the exciting possibility to observe X-ray emission from BH-NS mergers: $\sim 1-53$ event per year. The X-ray emission from these sources should also be brighter than from a NS-NS mergers, since the mass of the central BH could be much larger. The above rates, however, should be taken as indicative of upper limits. We have not taken into account selection effects such as background/foreground sources and the fact that not all BH-NS and NS-NS mergers seem to lead to an accreting system (e.g., Rosswog 2005; Belczynski et al. 2008). Moreover, in some cases, the X-ray afterglow from the burst could outshine the wind emission. Nevertheless, the possibility to get information on mergers of compact objects from electromagnetic signals remains, and it could bring important understanding of the physics of these systems.

Finally, our findings have implications for interpreting late time activity observed in GRB afterglows. We consider unlikely that fallback matter can be held responsible, since most of the mass is blown away. Even if $\sim 10\%$ of this matter can accrete all the way to the hole, it is very unlikely that it could produce the observed flares, which have an energy ($\sim 10^{49}-10^{46}$ ergs) comparable to that of the prompt emission (e.g. Campana et al. 2006). This would require that the eccentric tail is far more massive than the main disc (contrary to what is observed in simulations) or that the efficiency in converting accreted mass to energy is somehow strongly enhanced in the late fallback accretion. These arguments also apply to the late accretion from the main disc, which is highly super-Eddington (Metzger et al. 2008). We thus conclude that, in general, standard late time accretion is unlikely to account for the phenomena, like flares and plateaux, observed in GRB afterglows.

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